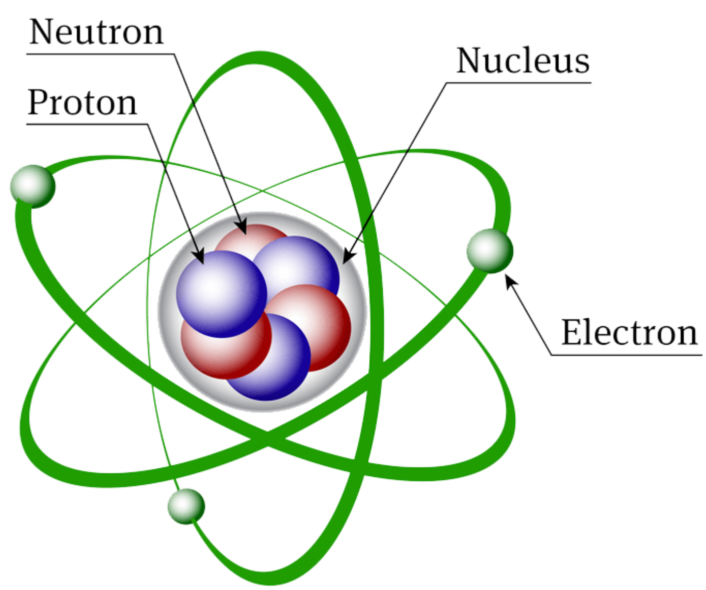
Structure of atom

All matter is composed of atoms, each of which has a central nucleus and one or more electrons that travel in orbits around the nucleus, like satellites around the earth. The nucleus contains one or more positively charged particles called protons. The positive charge of a proton is 'opposite' to the negative charge of an electron, in the sense that the total, or net, charge of the combination is zero. Thus, an atom that has the same number of electrons in orbit as it has protons in its nucleus is electrically neutral. The nucleus of every atom except that of hydrogen also contains one or more neutrons, which carry no electrical charge. The number of protons and neutrons in the nucleus of an atom uniquely determines the element it represents - iron, copper, oxygen, and so on - and all the atoms of a given element have identical nuclei.



Atomic Models:

Different atomic models were proposed to explain the distributions of these charged particles in an atom. Such as, (i) Thomson model of atom (ii) Rutherford's nuclear model of atom (iii) Bohr's model of atom.

Although some of these models were not able to explain the stability of atoms, two of these models, proposed by J. J. Thomson and Ernest Rutherford.

Historically, results observed from the studies of **interactions of radiations with matter** have provided immense information regarding the structure of atoms and molecules. Neil's Bohr utilized these results to improve upon the model proposed by Rutherford.

Two developments played a major role in the formulation of Bohr's model of atom. These were: (i) Dual character of the electromagnetic radiation which means that radiations possess both wave like and particle like properties, and (ii) Experimental results regarding atomic spectra which can be explained only by assuming quantized electronic energy levels in atoms.

De Broglie Matter Waves:

All matter particles like electrons, protons, neutrons, atoms or molecules have an associated wave with them which is called matter wave or pilot wave or De Broglie's wave.

The wavelength of the matter wave is given by, $\lambda = \frac{h}{p} =, \frac{h}{mv}$

Where m is the mass of the material particle, v its velocity and p its momentum. The above relation is known as De Broglie's wave equation.

Compton Effect:

X-rays are scattered by matter in two different ways

(1) Thomson Scattering or Coherent Scattering: In this process the X-rays are scattered by electrons without any change in their wavelength.

(2) Compton Scattering: In this process, the scattered X-rays consist of two components: one component has the same wavelength λ as the original incident X-ray and the other length λ'. This phenomenon in which there is change in wavelength of the scattered X-rays is called Compton Effect.

It was discovered by A.H Compton in 1923 during the scattering of X-rays with matter. Compton scattering is observed when X-rays of high energy fall on solid matter.

$$\lambda - \lambda' = \frac{h}{m_e c}(1 - \cos\theta)$$

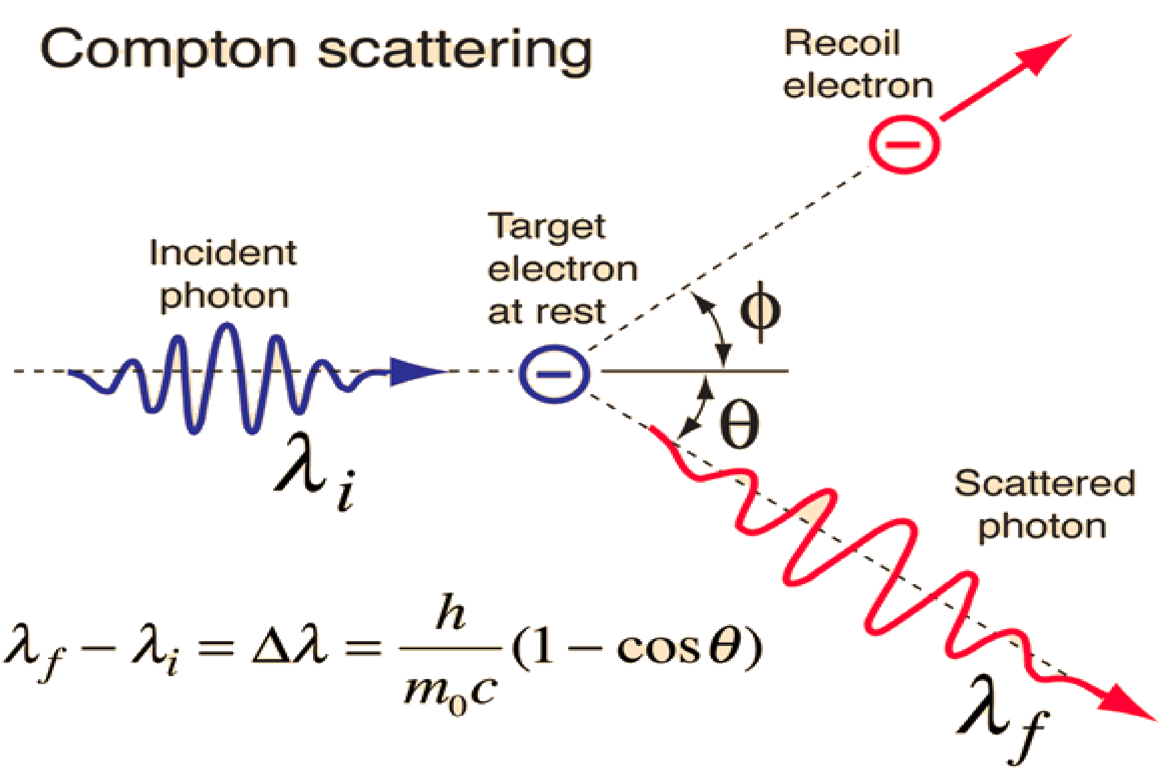
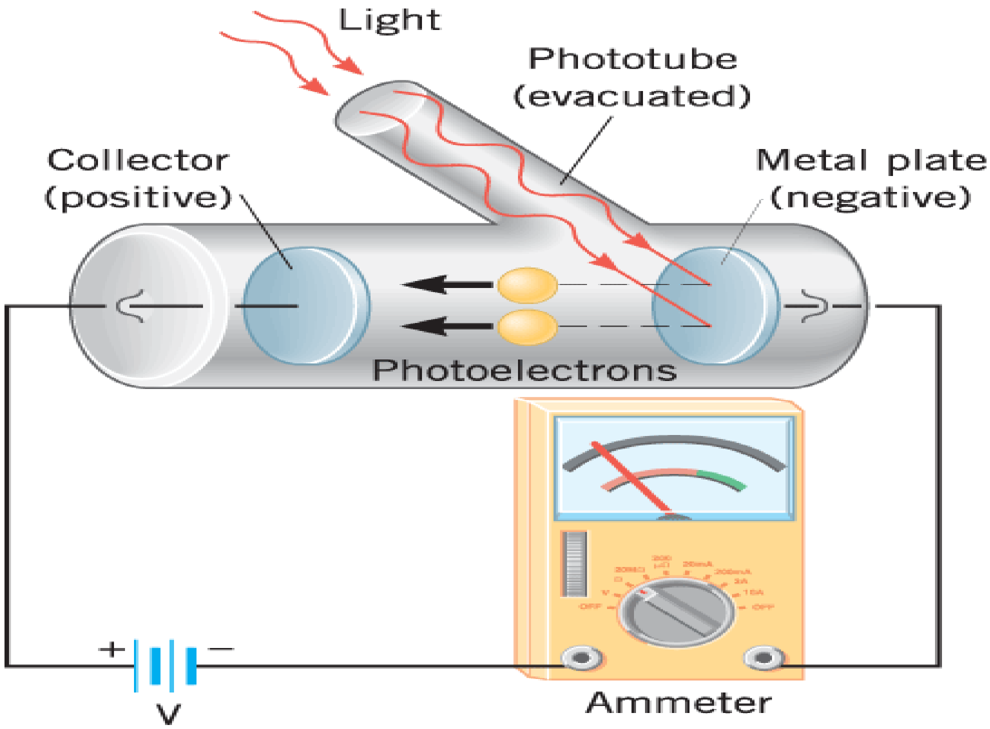


Photo-electric Effect:

When radiation such as ϒ-rays, x-rays, ultra-violate rays falls on a good number of substances i.e. metals, electrons are ejected from these substances. This phenomenon is called photo-electric effect. The electrons which are emitted is called photoelectrons.



Photoelectric Cell:

The device, working on photoelectric effect, which can transform light energy into electric energy is called photoelectric cell. Photoelectric cell of three types

1. Photo-emission cell
2. Photo-voltaic cell
3. Photo-conductive cell

Einstein Photoelectric Equation:

In Einstein's theory, radiation is regarded as a shower of photons, each of energy $h\nu$ moving in space with velocity of light when a single photon is incident on a metal surface; it is completely absorbed by an atom. The energy is utilized for two purposes:

- The energy for getting the electron free from the atom and away from metal surface. This energy is known as the photo electric work function of the metal and it is represented by Φ or ω_0.
- The balance of the photon energy is used up in imparting to the freed electron a kinetic energy of $\frac{1}{2} mv^2$.

In mathematical form, $h\nu = \omega_0 + \frac{1}{2} mv^2$…………………….. (1)

Where, $h\nu$= Energy content of each quantum of the incident light.

ω_0= Photo-Electric work function.

$\frac{1}{2} mv^2$ = Kinetic energy of the ejected photo electron.

Equation (1) is as the Einstein's Photo Electric equation.

Threshold Frequency:

Threshold frequency is defined as the minimum frequency of incident light which can cause photo electric emission i.e. this frequency is just able to eject electrons without giving them additional energy. It is denoted by v_o

Photo-Electric work function:

The photo electric work function is defined as the energy which is just sufficient to liberate electrons from a body with zero velocity. If the amount of energy of incident radiation is less than the work function of metal, no photo electrons are emitted. It is denoted by Φ. It is a property of material. Different materials have different values of work function.

Mathematically, work function of a material is given by,

$$\omega_0 = h\gamma_0 = \frac{hc}{\lambda_0} = \frac{3\times10^{8}\times6.63\times10^{-34}}{\lambda_0}$$

$$\omega_0 = \frac{19.87\times10^{-26}}{\lambda_0} \text{ Joule, } \lambda_0 \text{ in m}$$

$$\omega_0 = \frac{19.87\times10^{-16}}{\lambda_0} \text{ Joule, } \lambda_0 \text{ in } A^0$$

$$\omega_0 = \frac{19.87\times10^{-16}}{1.6\times10^{-19}\,\lambda_0} \text{ eV}$$

$$\omega_0 = \frac{12400}{\lambda_0} \text{ eV}$$

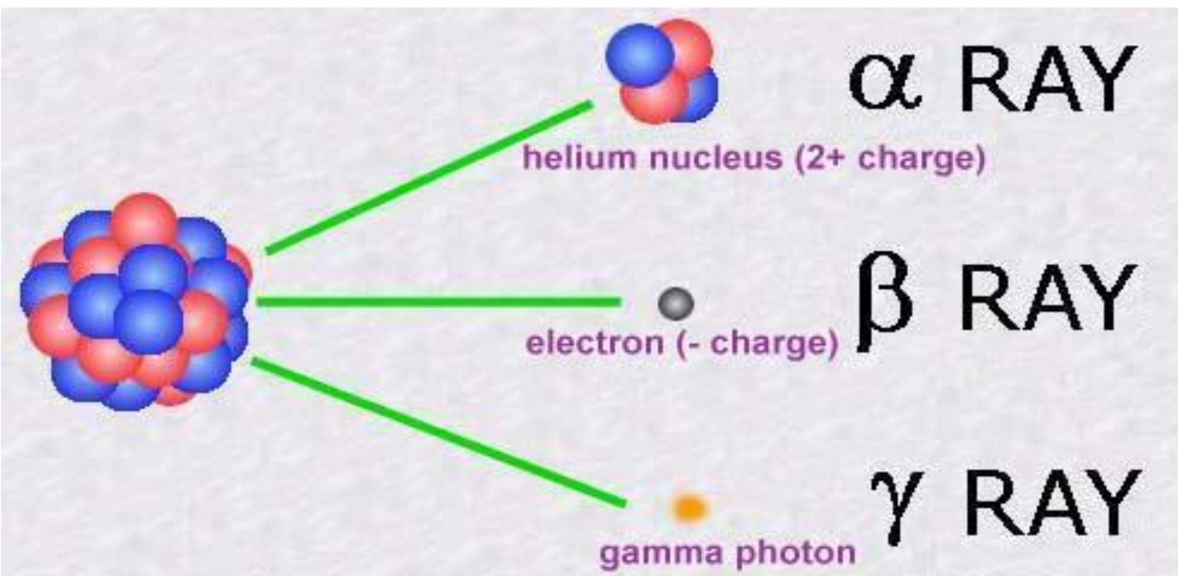
Problem:

What is the threshold wavelength for a tungsten surface whose work function is 4.5 eV?

Radioactivity

Radioactivity:

Radioactivity is the process where atomic nuclei release energetic subatomic particles. The phenomenon of spontaneous emission of powerful radiations exhibited by heavy elements is called radioactivity. Radioactivity is essentially a nuclear phenomenon. Those elements which exhibit this activity are called radioactive elements. Examples are: uranium, polonium, radium, radon, thorium, actinium.



Radioactivity was first discovered in 1896 by the French scientist Henri Becquerel, after which the SI unit for radiation, the *Becquerel*, is named. Becquerel discovered that uranium -92 gave out some kind of radiations which were highly penetrating, could affect photographic plate placed in the dark, even though a paper barrier. Subsequent experiments distinguished three distinct types of radiation –

- Alpha rays or α particles:
- Beta rays or β particles:
- Gamma rays or photons:

There are two types of radioactivity. One is natural radioactivity and another is artificial radioactivity

Radioactive Disintegration or Decay

Atoms of heavy elements like uranium, thorium, polonium and radium etc are constantly breaking up into fresh radioactive atoms with the emission of Alpha (α), Beta (β) and, Gama (γ) rays from their nuclei. In the process the original (or parent) atom disappears and gives rise to new (daughter) atom. The new atoms are also, in general, radioactive and hence spontaneously break up, in their turn, thereby leading to a long chain of different radioactive elements in the form of a series until an inactive element is reached. This spontaneous breaking up of the nucleus is known as radioactive disintegration.

From the radioactive law it can be written as,

$$\lambda N = dN/dT$$

It may be defined as the ratio of the amount of the substance which disintegrates in a unit time to the amount of the substance present.

That is, the probability of decaying a radioactive nucleus per unit time is called decay constant.

Units of radioactivity:

In radioactivity, the number of radioactive atoms disintegrate in unit time, i.e, $\frac{dn}{dt}$ is called the activity of a substance. The unit for measuring this activity is called the curie (Ci) which is defined as that quantity of a radioactive substance which gives 3.7×10^{10} disintegrations per second.

1 mili curie (mCi)= 3.7×10^{10} dis/sec.

1 micro Curie (μCi)= 3.7×10^{4} dis/sec.

The SI unit of activity is Becquerel (Bq) which is equal to 1 disintegration per second.

Another unit, Rutherford is defined as the quantity of a radioactive substance which gives 10^{6} disintegration per second.

α decay:

Whenever a radioactive nucleus breaks into a daughter nucleus with two neutrons and two protons is ejected from the nucleus of a radioactive atom. The particle is identical to the nucleus of a helium atom.

Alpha decay only occurs in very heavy elements such as uranium, thorium and radium. The nuclei of these atoms are very "neutron rich" which makes emission of the alpha particle possible.

$^{238}U_{92}$ ---> $^{234}Th_{90}$ + $^{4}He_{2}$.

The particle affect a photographic plate and they produce fluorescence when they fall on a substance like zinc Sulphide. They are deflected by electric and magnetic fields. This proves that they are charged particle.

β decay:

Beta decay is the radioactive process in which unstable atom can use to become more stable.

There are two types of beta decay. One is electron emission (Beta minus) and Positron emission (Beta plus).

During electron emission, a neutron in the atom's nucleus turns into a proton, an electron and an antineutrino.

$^{14}C_6 \dashrightarrow {}^{14}N_7 + e^- + Ve^-$ (anti neutrino)

During positron emission, a proton in an atom's nucleus turns into a neutron, a positron and a neutrino.

$^{23}Mg_{12} \dashrightarrow {}^{23}Na_{11} + e^+ + Ve^+$ (neutrino)

They affect photo graphics plates more strongly than α particle and they produce fluorescence in calcium tungstate. They are deflected by electric and magnetic fields and their direction of deflection indicates that they are negatively charged particles.

Examples of beta emitters commonly used in biological research are: hydrogen-3 (tritium), carbon-14, phosphorus-32, phosphorus-33, and sulfur-35.

γ decay:

Gamma rays are electromagnetic radiations of very short wave length ranging from 0.5A to 0.005A. They are classically produced by the decay of atomic nuclei as they transition from a high energy state to a lower state with the emission of electromagnetic radiation. Gamma decay does not change the mass or charge of the atom from which it originates.

They are not charged particles and they travel with the velocity of light. They are not affected by electric and magnetic fields but they can be diffracted by crystals. They produce fluorescence and affect photographic plates more intensely than β rays.

Examples of gamma emitters are cobalt-60, zinc-65, cesium-137, and radium-226.

Radioactive decay law:

In 1902, Rutherford and Soddy, after extensive studies formulated a law, known as the law of radioactive disintegration or decay. This law states that ―At any moment the number of radioactive atoms that disintegrate in unit time is directly proportional to the number of unchanged radioactive atoms remaining. If the rate of radioactive disintegration of atoms is dNdt if N is the number of unchanged atoms at time t, then

$$\frac{dN}{dt} \propto -N$$

$$\frac{dN}{dt} = -\lambda N$$

$$\frac{dN}{N} = -\lambda\, dt$$

Where, λ is the radioactive decay constant.

$$\int \frac{dN}{N} = -\lambda \int dt$$

$$\text{Log}_e N = -\lambda t + C \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where, C is the constant of integration.

Suppose, $N = N_0$ at time $t = 0$

Then

$$\text{Log}_e N_0 = C$$

From equation number (1)

$$\text{Log}_e N = -\lambda t + \text{Log}_e N_0$$

$$\text{Log}_e \frac{N}{N_0} = -\lambda t$$

$$\frac{N}{N_0} = e^{-\lambda t}$$

$$N = N_0\, e^{-\lambda t}$$

This is the law of radioactive decay or disintegration.

Half Life:

The half-life of a radioactive element is defined as the time during which the number of atoms remaining unchanged becomes half of its initial value.

We have, $$N = N_0 e^{-\lambda t}$$

By definition, when $$t = T_{1/2} \quad \text{(i.e. half life)}$$
$$N = \frac{1}{2} N_0$$

So, $$\frac{1}{2} N_0 = N_0 e^{-\lambda T_{1/2}}$$

So, $$\frac{1}{2} = e^{-\lambda T_{1/2}}$$

Thus, $$2 = e^{+\lambda T_{1/2}} \quad \text{(by inverting both sides)}$$

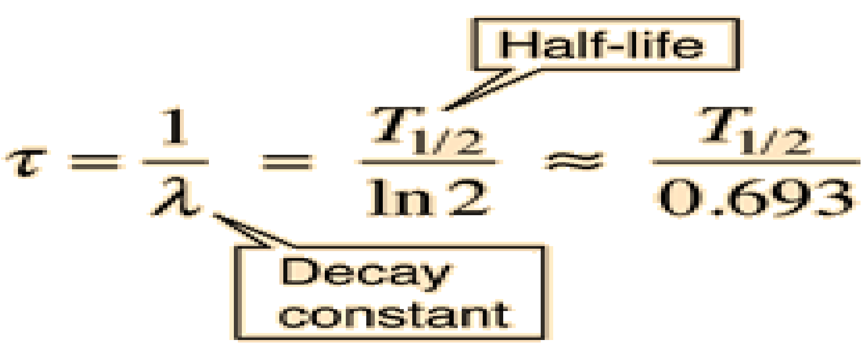
Now, taking 'logs to base e', known as 'natural logs', symbol $\log_e$ or ln:

$$\ln 2 = \ln e^{+\lambda T_{1/2}}$$
$$= (\lambda T_{1/2}) \ln e \quad (\text{since } \ln e^x = x \ln e)$$
$$= \lambda T_{1/2} \quad (\text{since } \ln e = 1)$$

So, $$\boxed{T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.69}{\lambda}}$$

Mean Life:

The mean or average life is the average lifetime of a radioactive atom before it decays. It is the sum of the lifetimes of all the individual nuclei divided by the total number of nuclei involved. Mean life is used to determine the total number of disintegrations or the emitted radiation.

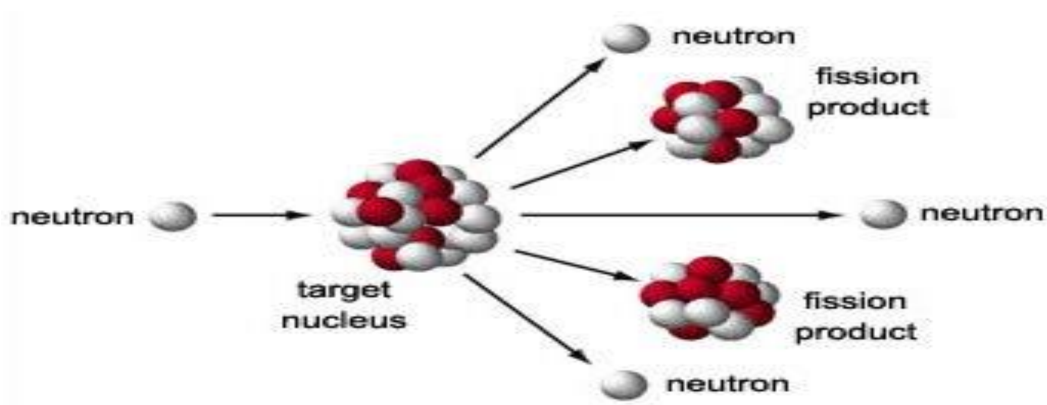


Nuclear Fission:

The division of a nucleus into two approximately equal parts is called nuclear fission. This process is initiated and accompanied by the emission of fast moving neutrons. The number of neutron released depends on the mode of fission and the energy of the neutrons which induce fission.

Example: When a uranium nucleus is bombarded by high energy neutrons or protons or deuterons, then fission takes place. This reaction can be represented as

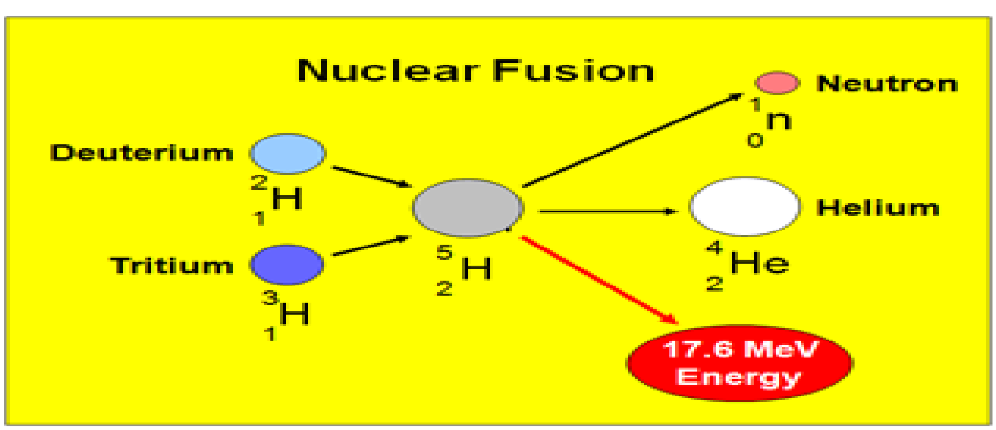
$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3\ ^{1}_{0}n + \text{energy}$$



The neutrons emitted as a result of fission process can be divided into two groups. (i)Prompt Neutrons (ii) Delayed Neutrons

Nuclear Fusion:

It is process of combining or fusing two lighter nuclei into a stable and heavier nuclide. In this case, large amount of energy is released because mass of the product nucleus is less than the masses of the two nuclei which are fused.



Derivation of Einstein's mass-energy relation:

We know from the second law of motion that rate of change of momentum is called force. So

$$F = \frac{d}{dt}(mv)$$

We know from the theory of special relativity that both mass and velocity vary.

$$F = \frac{d}{dt}(mv)$$

$$= m\frac{d}{dt}v + v\frac{d}{dt}m \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Suppose, force F creates displacement of dx of a body. So, work done = F. dx. Then the increase in kinetic energy (dE_k) of the body is equal to the work done (F. dx)

Suppose, force F creates displacement of dx of a body. So, work done = F. dx. Then the increase in kinetic energy (dE_k) of the body is equal to the work done (F. dx)

$$dE_k = F.\, dx$$

$$= \left(m\frac{d}{dt}v + v\frac{d}{dt}m\right).\, dx$$

$$\frac{dx}{dt} = v$$

$$= m\frac{dx}{dt}dv + v\frac{dx}{dt}dm$$

$$= mv\, dv + v^2\, dm \quad \ldots\ldots\ldots\ldots\ldots (2)$$

From the relation of mass and velocity

$$m = \frac{m_0}{\sqrt{1-\frac{v^2}{c^2}}}$$

Squaring both sides, we get

$$m^2 = \frac{m_0^2}{1 - \frac{v^2}{c^2}}$$

$$m^2c^2 - m^2v^2 = m_0^2c^2$$

$$\text{or, } m^2c^2 = m^2v^2 + m_0^2c^2$$

Differentiating both sides

$$2m.\, dm\, c^2 = 2m\, dm\, v^2 + 2v\, dv\, m^2$$

$$dm\, c^2 = (mv\, dv + v^2\, dm) \quad \ldots\ldots\ldots\ldots \text{(3)}$$

From (2) and (3)

$$dm\, c^2 = dE_K \quad \ldots\ldots\ldots\ldots \text{(3)}$$

It can be written as

$$dE_K \propto dm$$

If the object is stationary, then $v = 0$ and K.E = 0. In this condition $m = m_o$, but when the velocity of the body is v, then the mass is m.

$$\int_0^{E_k} dE_k = \int_{m_0}^{m} dm\, c^2$$

$$E_k = c^2 \int_{m_0}^{m} dm$$

$$E_k = c^2 \left[m \right]_{m_0}^{m}$$

$E_k = c^2 \ (m - m_o)$

$E_k = m c^2 - m_o c^2$

This is the relativistic formula for kinetic energy.

When the body is at rest, the internal energy stored in the body is $m_o c^2$. This energy is called rest mass energy

So, the total energy of the body

E = kinetic energy + rest mass energy

$E = E_k + m_o c^2$

$E = m c^2 - m_o c^2 + m_o c^2$

$E = mc^2$

This is Einstein's mass – energy relation.

Einstein's mass-energy equivalent law

In 1905 famous scientist Albert Einstein showed that matter and energy were actually identical. Matter can be transformed into energy. If a substance of mass m is completely transformed into energy, the amount of energy obtained is

$E = mc^2$, (here c is the speed of light = 3×10^8).

This is called the Einstein's mass-energy equivalent law.

Atomic Number:

The atomic number or proton number (symbol Z) of a chemical element is the number of protons found in the nucleus of an atom. It is identical to the charge number of the nucleus. The atomic number uniquely identifies a chemical element.

Mass Number:

The mass number (symbol A) also called atomic mass number or nucleon number, is the total number of protons and neutrons (together known as nucleons) in an atomic nucleus.

Mass number=protons + neutrons

Atomic Mass Unit (AMU):

The unified atomic mass unit or Dalton (symbol: u, or Da or AMU) is a standard unit of mass that quantifies mass on an atomic or molecular scale (atomic mass). One unified atomic mass unit is approximately the mass of one nucleon and is numerically equivalent to 1 g/mol.

Nuclear binding energy & Mass Defect:

It is the minimum energy that would be required to disassemble the nucleus of an atom into its component parts. These component parts are neutrons and protons, which are collectively called nucleons. The binding is always a positive number, as we need to spend energy in moving these nucleons, attracted to each other by the strong nuclear force, away from each other.

Thus, we have the binding energy of nucleus given by the equation

$$B.E = \Delta mc^2$$

Here, Δm represents the mass defect.

Proton and neutron are the constituent particles of nucleus. But the mass of a nucleus is found to differ from the sum of masses of proton and neutron .This difference in mass is known as **mass defect.**

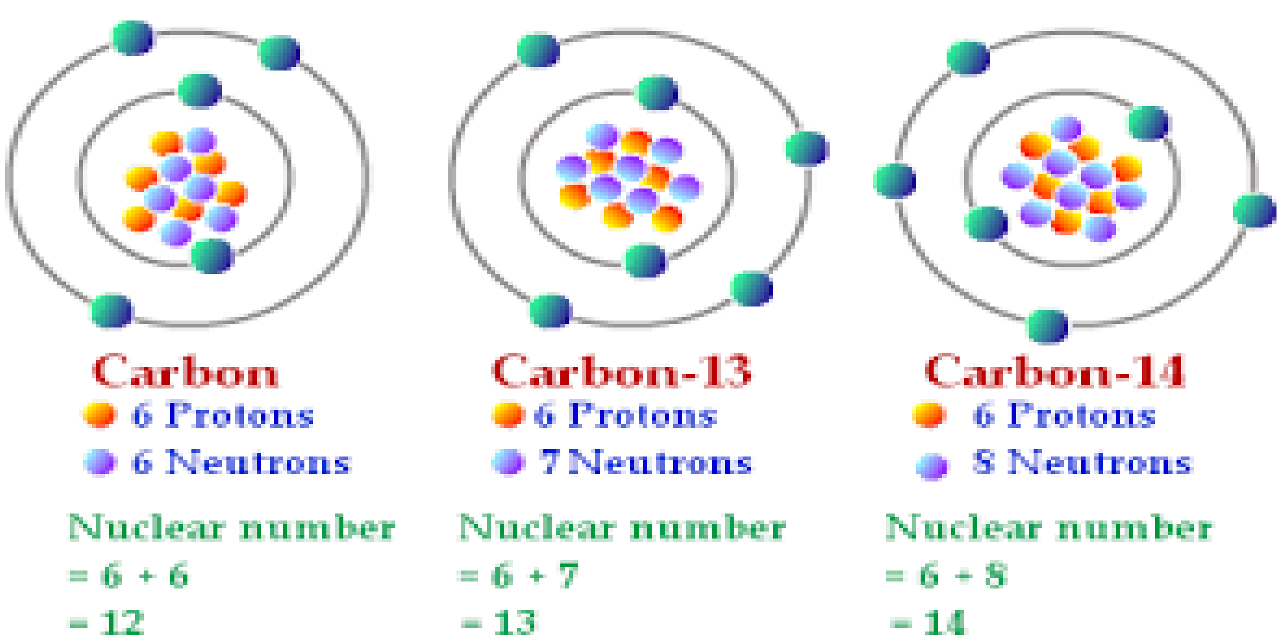
The original atomic mass found to be less than the sum of individual masses of its constituent particles. The actual mass is found to be less than the individual mass of proton and neutrons added together because energy is removed during the formation of nucleus. Mass defect which is the mass missing in the resulting nucleus represents the energy released during formation of nucleus

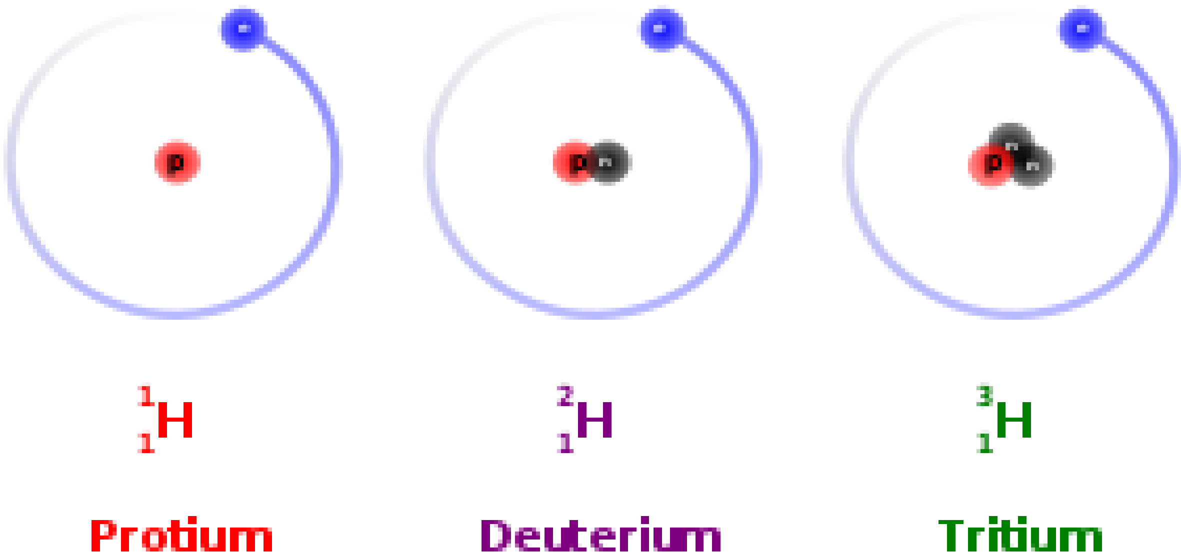
The mass defect is given by the formula

$$\Delta m = \left(m_n + m_p\right) - m_o$$

Isotope:

Isotopes are variants of a particular chemical element which differ in neutron number, and consequently in nucleon number. All isotopes of a given element have the same number of protons but different numbers of neutrons in each atom.





Isobars:

Isobars are atoms (nuclides) of different chemical elements that have the same number of nucleons. Correspondingly, isobars differ in atomic number (or number of protons) but have the same mass number. An example of a series of isobars would be ^{40}S, ^{40}Cl, ^{40}Ar, ^{40}K, and ^{40}Ca.